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Sapflow Database Reveals Density-Dependent Competition Among Woody Plants at Global Scale

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ABSTRACT

Though limiting resources differ among systems, water is limiting in most arid and many mesic systems, potentially allowing for direct measurement of competition by measurement of water uptake. Sapflow measurements provide a direct measure of water movement through plant stems, but, to our knowledge, sapflow has never been used to study density dependence and competition at large (regional or global) scales. Here, we examine a global database of sapflow measurements, the SapFluxNet database, for signs of density-dependent competition for water. We find that plant-level water uptake decreases with increasing competition from neighbours (specifically, neighbourhood basal area). Further analysis demonstrates that global-scale variability in annual sapflow can be largely explained ($R^2 = 0.522$) by the combination of average vapour pressure and neighbourhood summed basal area. This analysis provides a rare quantification of plant competition for a limiting resource inferred directly via measurements of resource acquisition (i.e., sapflow).

1 | Introduction

As precipitation becomes more variable and aridity increases in many regions across the world, it is increasingly important to understand the effects of water on ecosystem structure and function (Maestre et al. 2016; Saco et al. 2018). Water availability is a fundamental constraint on vegetation growth, especially in arid and mesic systems (Craine and Dybzinski 2013; Saco et al. 2018), and the interactions between vegetation and water in drought-seasonal ecosystems affect a wide variety of ecological and physical processes, including water and energy balance and resource connectivity (Wilcox et al. 2022). Many studies have investigated the relationship between water-limitation and vegetation density (Craine and Dybzinski 2013; Sankaran et al. 2005). For example, Sankaran et al. (2005) discovered a significant relationship between precipitation and potential woody cover in African savannas, reflecting the intimate relationship between vegetation communities and water limitation in drought-seasonal tropical ecosystems. Similarly, field and satellite data from regions of the arid and semi-arid United States experiencing woody plant encroachment show signs of competition-constrained canopy cover (Archer et al. 2017; Ji et al. 2019; Pierce et al. 2019; Roberts and Hanan 2024; Wojcikiewicz et al. 2024). However, these earlier analyses of competition-limited canopy cover have used indirect proxies of limiting resources, such as stem count, canopy cover, or growth rate which are the outcomes of competition rather than the process itself. Rarely has previous work explored competition among woody plants in the field using direct measurements of limiting resource acquisition

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(but see, for example, Lagergren and Lindroth 2004; Lundblad and Lindroth 2002). Here, we attempt to do that at a macroscale using a global-scale dataset of woody plant transpiration (i.e., sapflow) available in the SapFluxNet database (Poyatos et al. 2021).

Competition is typically defined as interactions between organisms that lead to reductions in the fitness of individuals (Wall and Begon 1985). Thus, many studies quantify competition effects in terms of survival, growth and reproductive output which, in reality, are indirect proxies for the competitive process of resource acquisition (Schoener 1983; Sih et al. 1985). By focusing on the ability of plants to acquire a critical resource (i.e., water in water-limited environments), we endeavour to build more direct insight into the process of resource preemption by competing populations of plants, expanding on previous indirect studies of competitive outcomes. In this context, we argue that sapflow-based measurements may have the potential to uncover the 'currency of competition,' elucidating the intimate relationship between community-scale competition processes and the limited resources that make competition necessary in the first place; that is, investigating the process of competition rather than competitive outcomes.

In drylands and drought-seasonal environments, we anticipate significant interactions between vegetation structure and water resources. Water may impact vegetation structure and function via facilitative or competitive processes (Dohn et al. 2017; Ji et al. 2019; Kulmatiski and Beard 2022; Saco et al. 2018; Simonin et al. 2007). Although facilitation is common in drylands, particularly due to the beneficial impacts of larger plants on smaller or juvenile plant growth and survival (Dohn et al. 2013), competition likely dominates among adult woody plants because of niche similarity and spatial proximity of roots competing for limited water (Wojcikiewicz et al. 2024). Some studies have investigated the relationship between density and plant water use in experimental settings (Hagishima et al. 2007) and using sapflow across smaller spatial extents (Lagergren and Lindroth 2004; Lundblad and Lindroth 2002), but we are unaware of studies seeking to detect signs of competitive interactions at larger (e.g., global) scales via meta-analysis of field-scale sapflow data. Plant water use (i.e., transpiration) can be studied using leaf-level measurements of stomatal conductance (Clearwater et al. 2009; Poyatos et al. 2021), individual plant-level measurements of transpiration rate (i.e., sapflow; Clearwater et al. 2009; Hagishima et al. 2007; Liu et al. 2011; Poyatos et al. 2021; Tyree 2003), and ecosystem-level water flux measurements using, for example, the eddy covariance technique (Jasechko et al. 2013). For our purposes, neither leaf-level nor eddy covariance approaches provide ideal measurements of plant water use, because leaf-level water flux measurements do not directly measure whole plant water acquisition, and eddy covariance methods integrate larger populations of plants and include evaporation from soil and transpiration of non-woody plants (Wilson et al. 2001). Sapflow measurements, on the other hand, isolate individual woody plants (stems), making sapflow well-suited to exploring the impacts of neighbourhood competition on the ability of individuals to access water resources. Thus, we reasoned that sapflow data may be especially useful for detecting density-dependent (i.e., competitive) effects on individual plant water use. The SapFluxNet database (Poyatos et al. 2021) compiles plant-level sapflow measurements at global scale, offering the opportunity to ask population-level, competition-based questions, using individual-level water uptake data.

Our goals are (1) determine whether signals of density-dependent competition exist in sapflow data, and (2) characterise the relative impacts of climate and plant density on sapflow. We hypothesize that signals of density-dependent competition among plants will emerge in sapflow data following normalisation of raw sapflow measurements to account for variability in stem-size (i.e., basal area) and variability among sites in mean annual precipitation. Furthermore, we predict that signals of competition will emerge more strongly in more arid environments, where water is generally the most limiting resource, than in more mesic (i.e., wetter) environments.

2 | Methods

2.1 | SapFluxNet

Sapflow data were analysed in R 4.1.0 using the SapFluxNetR package (Granda et al. 2021; R Core Team 2021). Sapflow data were compiled in the SapFluxNet database from numerous experimental sites using standardised QA/QC and aggregation procedures (see Poyatos et al. 2021 for details). Sites are distributed across global biomes (Figure 1) and multiple stems are instrumented within each site. For our analysis, we retain site-level climate and competition variables (see below) as well as stem-level sapflow measurements. Measurements in the SapFluxNet database range from the early 1990s to the late 2010s; however, instrumented stems differ in their lengths of collection time (Poyatos et al. 2021). Therefore, to facilitate comparisons across many sites, we standardised sapflow measurements by computing annual median sapflow values for all instrumented stems. Median sapflow values were used to mitigate the impact of outliers remaining in the database even after QA/QC controls. Both diurnal and nocturnal sapflow measurements were included in this calculation. Next, the annual median sapflow values were mean-averaged across all years of available sapflow measurements to assign long-term (i.e., annual) mean transpiration fluxes to each individual stem. Because sites in the SapFluxNet database differ in their observation time from less than 1–16 years of data, averaging first within years then across years provided single annual averages for each site, without inflating representation of longer-term sites. To ensure averaging across years did not bias sapflow measurements, analyses were repeated using individual median sap flow measurements, with year as a covariate. We found negligible temporal impacts on focal relationships, and thus continued analysis with sapflow measurements averaged across all years of data available (Data S1).

In addition to sapflow measurements, associated metadata from the SapFluxNet database were averaged at annual scales and retained for each site. These metadata included site-level mean annual precipitation (MAP, mm y^{-1}), mean vapour pressure deficit (VPD, kPa), mean solar radiation intensity (RAD, W m^{-2}), and mean air temperature (MAT, °C). In addition, we retained data on species and basal area of each instrumented stem, biome designation of instrumented sites, and locally

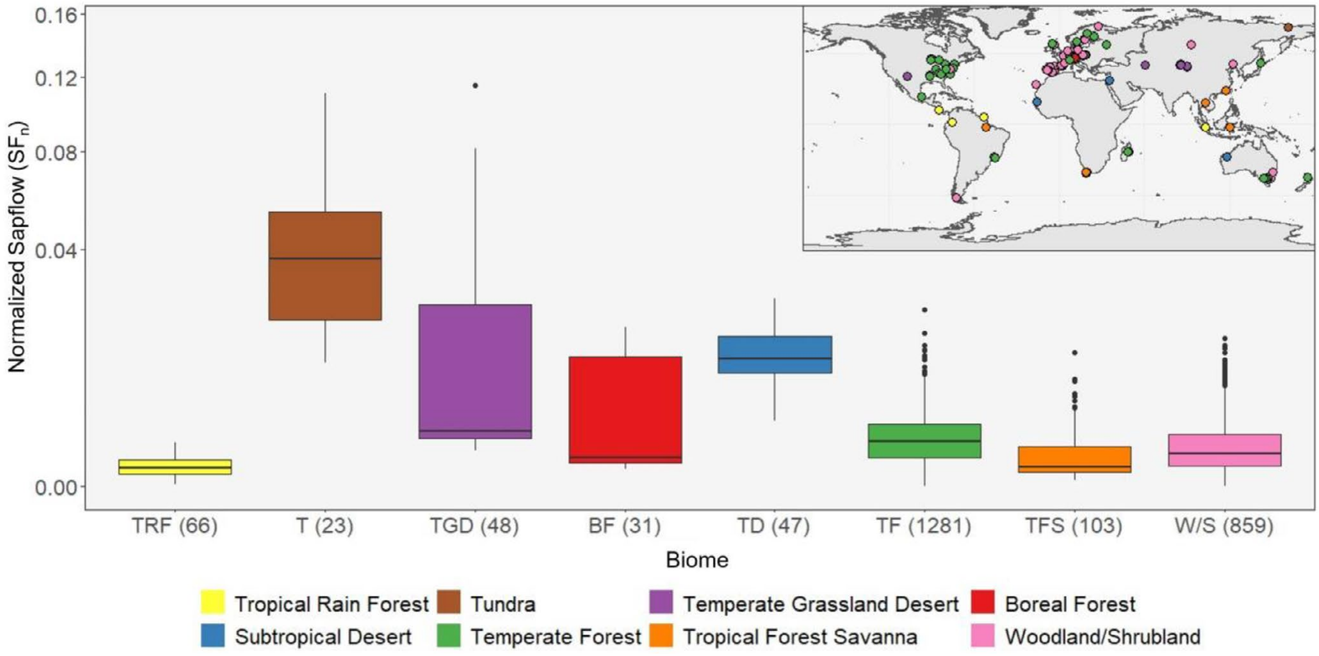

FIGURE 1 | Box plots showing median annual SF_n ($mL/h/m^2/mm$), and interquartile ranges across each biome in the SapFluxNet database. Spatial distribution of SapfluxNet sites used in this study (inset). Number of instrumented stems in each biome is shown in parentheses by *x*-axis labels. Note square root transformation of *y*-axis to improve visualisation of means and outliers. This figure shows the full dataset, but note the filtering of observations during analysis.

summed basal area (henceforth, BA_n) and sapwood area. BA_n is standardised to units of $m^2\ ha^{-1}$ in the SapFluxNet database. Although standardised, BA_n is computed for entire stands; thus, individual neighbour sizes and locations are unavailable, making the calculation of more complex measures of neighbourhood competition (e.g., the Hegyi index; Daniels 1976) impossible. Although this is a limitation of SapFluxNet, most sites contain sapflow data for species that make up at least 90% of total stand basal area (Poyatos et al. 2021), suggesting reliable sampling of sapflow across stands.

We adopted an external aridity index product (Trabucco and Zomer 2019) to assign aridity index values to each location, and instrumented stems in sites with MAT below 0°C were excluded from analysis. Further, some instrumented stems returned sapflow values below zero, indicating either instrument failure or hydraulic redistribution (Scholz et al. 2002). Removal accounted for the loss of 461 stems out of 2458 total. However, almost all of these removals were due to $MAT < 0$ (426 out of 461 removals), since consistently below freezing temperatures produce unique hydrological dynamics associated with permafrost, short-growing seasons, and freeze–thaw cycles (Black et al. 2021). We removed these individuals to focus our analysis on transpiration rates in ecosystems not subject to long winters or permafrost.

2.2 | Sapflow Normalisation Procedures

We normalised sapflow annual mean values in two steps to reduce variability associated with differences in stem size and water availability among sites. (i) Sapwood area normalisation: we first reduced the impact of variable stem sizes within and across sites by dividing the calculated annual mean sapflow by sapwood area of the measured stem, thus converting annual average sapflow (in mL/h for the stem) into sapwood normalised sapflow ($mL/h/m^2$; Cermak and Nadezhdina 1998). (ii) Normalised sapflow rain-use efficiency: we then further reduced impacts of difference in rainfall among sites by dividing the sapwood normalised sapflow by mean annual rainfall (MAP), thus converting sapwood normalised sapflow (in $mL/h/m^2$) into normalised sapflow rain-use efficiency (in $mL/h/m^2/mm$). We assessed the relationship between MAP and BA_n to avoid producing spurious relationships and found only limited correlation ($r = 0.23$; Data S2). These normalisation steps facilitated combined analysis of data from larger and smaller stems and comparisons across rainfall gradients. We chose to include mean annual precipitation in the response variable (i.e., as part of the normalisation), rather than select it as a predictor variable, because our hypotheses rely on controlling for water availability; without normalising by precipitation, it was unclear what effects to predict from BA_n (Data S1). We also considered normalising by aridity, but this approach would have made it difficult to interpret relationships between our normalised index of sapflow and environmental variables like VPD due to the strong correlation between aridity and VPD. Herein, we refer to measurements normalised for sapwood area and mean annual rainfall as 'normalised sapflow' (SF_n), although we continue to use 'sapflow' when referring to the movement of water through stems separate from our normalised index.

2.3 | Analysis

SapFluxNet global sapflow data are concentrated in temperate forests and woodland/shrubland biomes, but all biomes have >20 instrumented stems (Figure 1). Subsequent analyses focus on global scale relationships between SF$_n$ in response to climate and basal area. A preliminary bivariate scatterplot indicated the relationship between SF$_n$ and neighbourhood basal area (BA$_n$, Figure 2A). To quantify this relationship, we fit a linear-mixed effects model (log SF$_n$ ~ log BA$_n$ + soil + terrain + (1 | site)) with site as a random effect using the lme4 package in R (Bates et al. 2015). We included soil and terrain covariates to control for their effects on plant sapflow rates, although we expected rainfall to have a much stronger influence on sapflow. Given our interest in climate effects on sapflow, we also plotted SF$_n$ against the aridity index at each site (Figure 2B). Although a trend is present in the sapflow-aridity index plot, only Spearman correlation was assessed for the aridity index data due to violations of linear model assumptions and exclusion of the aridity index in subsequent analysis in favour of component climate metrics (VPD, MAT, etc.).

Initial scatterplots and linear analysis suggested both BA$_n$ and climate effects on SF$_n$, but these linear models would not allow for anticipated non-linear functional relationships between sapflow and environmental factors. Instead of continuing with parametric modelling approaches, we selected a random forest model to relate sapflow, climate variables, and BA$_n$. Random forests provide results analogous to generalised linear models, but allow for non-linear relationships and unbalanced data. Further, random forests iteratively subsample data and predictor variables and average decision tree predictions to prevent overfitting. Given the method's ability to fit non-linear relationships and handle unbalanced and non-normal data (Ziegler and König 2014), we determined random forest models suited the SapFluxNet data. We selected three annual averaged climate variables based on a priori expectations that they will impact plant-level transpiration (MAT, VPD and RAD). Selection of these variables allowed us to explore the interactive effects of climate on sapflow in more detail than the aridity index alone (Arora 2002; Valiantzas 2006). The three climate variables, together with BA$_n$, were provided as independent variables in the random forest regression model, using an even training/testing split of 50% to protect against overfitting.

Random forests are unable to relate SF$_n$ observations to predictor variables with missing values. This is problematic because a missing value in even one predictor value invalidates the inclusion of an entire SF$_n$ observation in the model. Given this sensitivity to missing data, missing data (VPD, BAn) at a small number of individual sites (17/152 analysed sites) were imputed using the median for the variable containing missing data. Imputation was not done for the response variable (SFn). Model results did not change significantly with or without imputation (Data S3), suggesting that imputation did little to change variable distributions, while facilitating the inclusion of more SF$_n$ observations into the model. We fit the random forest model using the ranger package in R (Wright and Ziegler 2017) and tuned hyperparameters across 5 cross validation folds. Random selection of hyperparameters within a grid is often used to minimise bias in machine learning models while optimising model fits (Pedregosa et al. 2011). Accordingly, we tuned random forest hyperparameters using the grid search approach. To assess variable importance, model variables were ranked based on the impurity option in the ranger package. We chose impurity because it ranks predictor variables according to their ability to discriminate training data into accurate predictions (Wright and

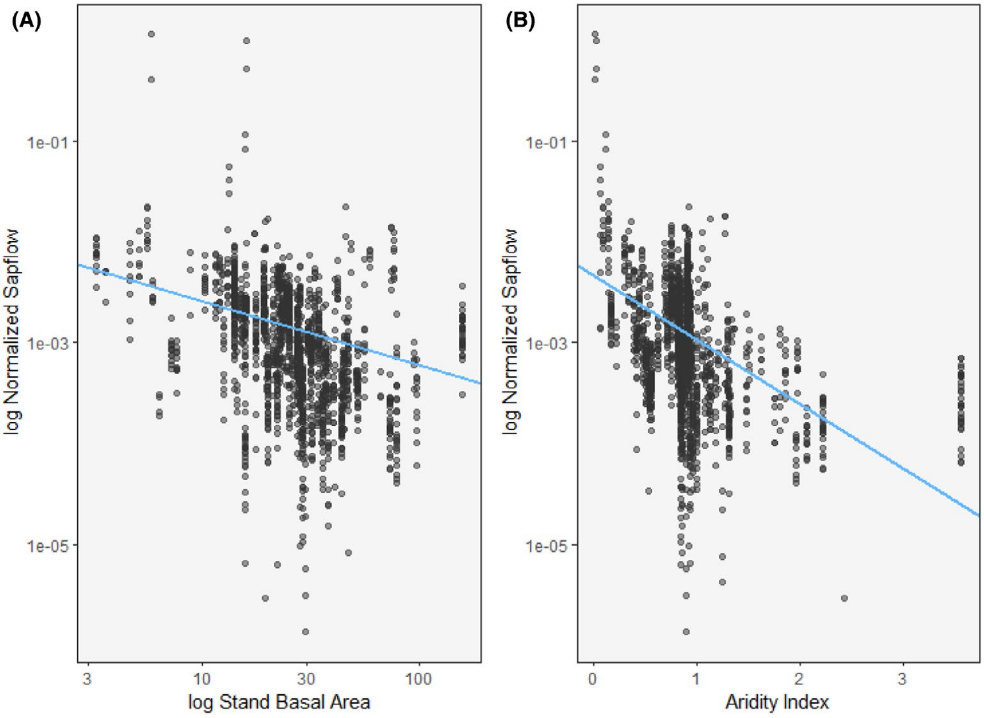

FIGURE 2 | Scatterplots of SF$_n$ (mL/h/m^2/mm, log-scale) against (A) neighbourhood summed basal area (BA$_n$, m^2 ha^{-1}) and (B) the aridity index (where arid sites have lower AI). Mixed-effects regression in (A) shows the global intercept and slope (slope = −0.63, $p = 0.008$; intercept = −1.96, $p < 0.001$). Only Spearman correlation ($r = -0.37$, $p < 0.00$) is shown in (B) due to violations of regression assumptions and the exclusion of aridity index in subsequent analysis.

Ziegler 2017), thus indicating the strength of predictor-sapflow relationships. Finally, partial dependence plots were used to visualise variable effects on sapflow. Due to the stochastic hyperparameter tuning and training/testing split in our random forest approach, we report results of ensemble predictions (200 iterations). The use of 200 iterations protected against overfitting by exploring relationships across the range of possible input data. Therefore, we have confidence in the general patterns emerging in the partial dependence plots, even though exact predictions differ across random forest iterations.

3 | Results

3.1 | Linear Analysis

A mixed effects model for the variation in sapflow as a function of stand basal area (Figure 2A) provides significant coefficients and suggests a strong relationship between SF_n and competition among plants, after accounting for site-level random effects, terrain, and soil texture (slope = −0.63, $p = 0.008$; Figure 2). Similarly, the Spearman correlation demonstrates a negative correlation between site-level aridity and SF_n ($r = -0.37$; $p < 0.001$; Figure 2B). Taken together, these results indicate a negative relationship between plant transpiration and neighbourhood basal area, and decreasing SF_n between arid and mesic systems. However, such bivariate relationships do not represent interactions among variables, motivating additional analysis.

3.2 | Random Forest Analysis

Random forest models between sapflow, BA_n, MAT, VPD and RAD explain, on average, ~50% of variation in the sapflow data (avg. $R^2 = 0.522$), with low root-mean square error (avg. RMSE = 0.0303 mL/h/m^2/mm). Partial dependence plots (PDPs) of the random forest model demonstrate trends in sapflow-climate and competitive relationships, with variable importance ranked VPD > BA_n > MAT > RAD (Figure 3). A clear increase in SF_n occurs with increasing values of VPD, representing the impact of increasing atmospheric demand in more arid locations. The PDP for BA_n, meanwhile, illustrates that sapflow decreases with increasing BA_n (Figure 3, particularly in the range

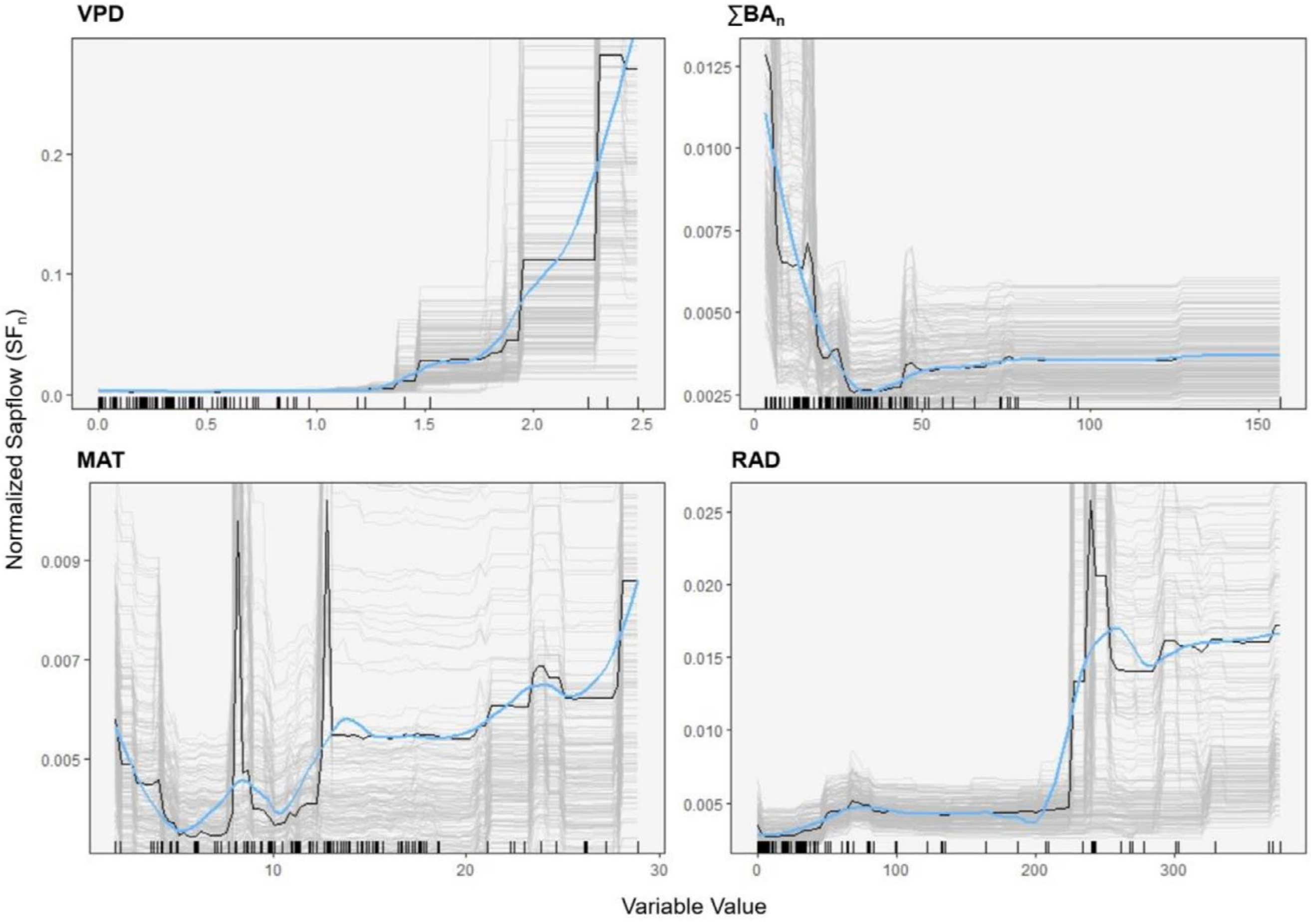

FIGURE 3 | Partial dependence plots (PDPs) from random forest model showing the sensitivity of SF_n (mL/h/m^2/mm) to mean annual vapour pressure deficit (VPD, kPa), competing neighbour stand basal area (BA_n, m^2 ha^{-1}), mean annual temperature (MAT, °C), and mean annual solar radiation intensity (RAD, W m^{-2}). PDPs are ranked according to variable importance from top-left to bottom-right (importance values: VPD = 0.672, BA_n = 0.122, MAT = 0.0918, RAD = 0.0620). Rug plots of random forest training data distributions are plotted on the bottom of PDPs. Black lines represent average sapflow responses across all ensemble members. Blue lines are LOESS smoothed curves of average changes, while grey lines are individual partial dependence curves of all 200 random forest models (RF model performance: Test $R^2 = 0.523$ and avg. test RMSE = 0.0303).

0–30 $m^2 ha^{-1}$), indicating the role of competition with neighbours in limiting resource acquisition. When modelled together (Figure 4), VPD and BA_n impact sapflow consistent with their individual effects (Figure 3), but with larger SFn sensitivity to VPD than BA_n (Figure 4). Remaining predictors, RAD and MAT, moderately increase SF_n, likely due to differences in seasonality across the database, with high latitude sites experiencing longer periods with cold temperatures and low solar intensity when plants tend to be dormant. The 200 iterations of the random forest ensemble show considerable variability associated with stochastic hyperparameters and data splits (Figure 3), but in most cases the general shape of sapflow sensitivity responses are consistent among ensemble members. This increases our confidence in the use of the random forest approach in determining variable effects on SF_n.

4 | Discussion

At the near global scale of the SapFluxNet database, our hypotheses of sapflow density were largely supported by our results. Competition among woody plants is clearly visible in SF_n data in both linear (Figure 2) and random forest (Figure 3) results. In particular, while vapour pressure deficit (VPD; representing atmospheric demand for water) has the strongest effect on sapflow, local basal area (BA_n; representing neighbourhood competition) is the second most important variable in the random forest model, ahead of other potential drivers, including mean annual temperature (MAT) and mean solar radiation intensity (RAD). The interactive effects of the two primary drivers (VPD and BA_n) are shown in Figure 4 where, as BA_n increases in the range 0–40 $m^2 ha^{-1}$, annual average sapflow measurements show clear declines, suggesting that water (i.e., resource) acquisition is reduced by root zone competition with neighbours. Overall, our results provide direct evidence for plant competition reducing resource acquisition, confirming a basic tenet of community ecology (e.g., Craine and Dybzinski 2013) using sapflow measurements. This result is particularly novel in that, to our knowledge, field-based detection of competition among plants is typically inferred via indirect proxies (e.g., reduction in growth rate) rather than direct measurements of the limiting resource.

The impact of increasing BA_n on sapflow is particularly visible at low basal area ($< 40\,m^2 ha^{-1}$). Above that threshold, BA_n has little additional effect on sapflow. While the reasons for this threshold are not clear from our analysis, we hypothesise that sites supporting high-density vegetation (e.g., rainforests) are also in regions that rarely experience water limitation, and thus where competition for water is less prevalent. Thus, the lack of BA_n effects in dense forest stands likely reflects limitation by, and competition for, other key resources, such as nutrients and light, which are not directly reflected in measurements of sapflow. Therefore, the long right tail of the SF_n- BA_n relationship

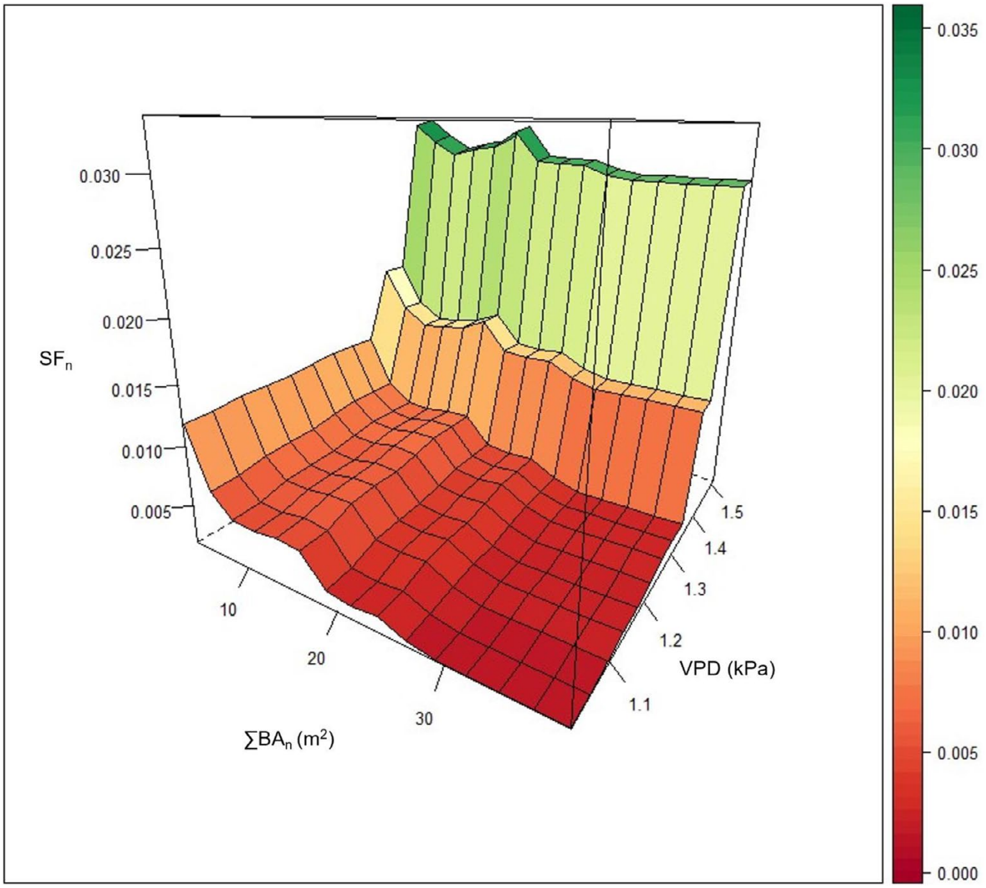

FIGURE 4 | 3D partial dependence plot from random forest showing interactive effects of basal area (BAn, m^2) and vapour pressure deficit (VPD, kPa) on SF_n ($mL/h/m^2/mm$). VPD and BA_n axis ranges chosen to visualise interesting portions of the SFn ~ BAn + VPD relationship ($BAn < 40m^2$; $1.0\,kPa < VPD < 1.55\,kPa$). Partial dependence values of SF_n are represented on the y-axis as well as the colour gradient.

represents values of SF_n independent of competitive, density-dependent effects (Figure 3).

We addressed the scarcity of data in drylands by restricting our analysis of the interaction between BA_n and VPD to VPD <1.5 (Figure 4). Though this approach was imperfect, it allowed us to generalise with greater confidence, at least within the range of VPD where sapflow measurements are better represented. To this end, the interaction between BA_n and VPD elucidates their individual effects on SF_n (Figure 4). Increases in BA_n, for example, are associated with decreases in SF_n across the range of VPD, but, surprisingly, the SFn $-BA_n$ relationship does not steepen at higher values of VPD (Figure 4). This result indicates that VPD is more responsible for SF_n values than BA_n under drier atmospheric conditions (when annual average VPD approaches ~1.5 kPa). At these high VPD values (i.e., high aridity), density-dependent competition likely decreases in importance as aridity increasingly drives transpiration. These results are consistent with the idea that facilitation, as opposed to competition, becomes the more prevalent mechanism of community interaction in highly stressed systems (stress-gradient hypothesis; Maestre et al. 2009). Therefore, the BA_n and VPD interaction illustrates not only the combined effects of density-dependent competition and aridity on sapflow, but also the relative importance of these two drivers of sapflow (Figure 4).

Though solar insolation (RAD) and mean annual temperature (MAT) are less important in the random forest model than VPD and BA_n (Figure 3), they also affect sapflow according to expectations, at least in their general direction of effect. Sapflow increases with RAD, corresponding to limitations on photosynthetic rates and evaporative demand associated with short growing seasons and shorter day lengths at higher latitudes. Likewise, while the MAT effect is both small and quite variable, the increase in sapflow with MAT reflects correlations between air temperature and both tree physiological activity and evaporative demand. Importantly, RAD and MAT affect SF_n across a much more restricted range than VPD (Figure 3), suggesting that RAD and MAT are far less impactful on SF_n values than VPD.

Though our results provide compelling evidence for direct competition among woody plants for water, we acknowledge limitations of the SapFluxNet database and our approach. We chose to normalise sapflow by MAP to facilitate interpretation of BA_n effects. This approach worked due to the low correlation between MAP and BA_n in the SapFluxNet database (Data S2), but we urge caution when normalising by MAP due to possible correlations in other datasets. Sites in the SapFluxNet database encompass a wide array of biomes and climatic conditions, but data is skewed to temperate forest and woodland/shrubland biomes (Figure 1). Despite the inclusion of some dryland sites in the database, very arid ecosystems are under-represented, in part due to the technical difficulty of measuring sapflow on smaller stems and arid-adapted shrubs (Xia et al. 2008). Including additional observations from arid ecosystems in the SapFluxNet database might help confirm our findings of density-dependent sapflow signals. In addition, some of the sites in the SapFluxNet database do not measure sapflow across an entire year, potentially biasing results in highly seasonal systems. While we chose to include all sites in our analysis to leverage the available data as much as possible, a sensitivity analysis (Data S4) suggests that our conclusions are not sensitive to this potential bias. Finally, our approach was to average sapflow data within sites and at annual scales to avoid over-representation of heavily instrumented sites in the analysis, but potentially removing some of the spatial and temporal fine-grain variation in sapflow rates within individual sites (see Data S1). We attempted to quantify SFn $\sim \sum BA_n$ relationships within sites, but only four sites in the SapFluxNet database contained sufficient information to facilitate within site analysis and variability in $\sum BA_n$ at these sites was low (Data S5).

5 | Conclusion

Analysis of global sapflow data allowed us to detect and quantify the impact of neighbourhood density on transpiration in focal trees: a unique demonstration at macroscales of competition among woody plants reducing resource acquisition in the field. Climatic variables, including vapour pressure deficit and solar radiation input, also impact sapflow values, emphasising the primary importance of atmospheric demand on transpiration, particularly in more arid regions. These results agree with key ecological principles regarding community competition for limited resources and demonstrate the utility of sapflow in global cross-site comparisons. While this analysis focused on detection of competition among woody plants at the macroscale of the SapFluxNet database, future work could enhance site-scale inference of competition through experimental manipulation of competitive neighbourhoods around sapflow measurements within individual sites. As aridity and precipitation variability increase in many regions across the world, we anticipate increasing water limitation and thus decreasing carrying capacity for woody plants (Roberts and Hanan 2024; Wilcox et al. 2022). Sapflow measurements provide an opportunity to investigate the underlying mechanisms of resource preemption driving vegetation community responses to changes in climate, especially in arid environments where woody plants are competing for limited soil water resources.

Author Contributions

T.R. conducted formal analysis, conceptualised research and project methodology, and wrote the first draft of the manuscript. N.P.H. provided project guidance and contributed to writing and editing of the manuscript.

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Data Availability Statement

SapFluxNet data and most ancillary data used in this analysis are available from the SapFluxNet website (https://sapfluxnet.creaf.cat; doi.org/10.5281/zenodo.3971689). Aridity index is available in the Global Aridity Index and Potential Evapo-Transpiration Database (https://figshare.com/articles/dataset/Global_Aridity_Index_and_Potential_Evapotranspiration_ET0_Climate_Database_v2/7504448/5; doi.org/10.6084/m9.figshare.7504448.v5). All data and code are available in a Zenodo repository (doi.org/10.5281/zenodo.14721376).

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ele.70167.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.